INSULATION AND DIELECTRIC BREAKDOWN DESIGN CONSIDERATIONS IN SUB-ATMOSPHERIC ENVIRONMENTS

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Abstract

A detailed knowledge of electrical insulation and high voltage design techniques is essential if reliable high voltage systems are to be designed and manufactured for use in sub-atmospheric environments. The trend is towards more advanced systems operating at higher voltages in compact, economical packages that have been submitted to a battery of diagnostic techniques to ensure a high quality assembly. The purpose of this paper is to present an overview of high voltage electrical/electronic design considerations required to specify and apply electrical insulation to high-voltage parts, components and systems used in sub-atmospheric environments. Operating voltage, frequency, temperature, ambient gas composition, pressure, radiation, and structural requirements must be known when designing insulation for high voltage equipment.

I. BACKGROUND

The primary purpose of an electrical insulation is to isolate one conducting surface from another and their surroundings, restricting current flow to the conductors. Many insulation designs have the additional functions of supporting the parts and structural components and also serve in efficient heat transfer from the parts to a thermal controlled surface. High voltage systems require special precautions because of the ever-present possibility of gas discharge phenomena in sub-atmospheric environments.

As a first cut, voltage considerations can be grouped. It should be noted that practices recommended at the lower voltages also apply to the higher voltage ranges.

A. Zero to 50 V

When the appropriate conditions exist corona can occur at any voltage level. The zero to 50 V region is usually considered corona-free for dc voltages and low frequency ac peak voltages (less than 500 Mhz). This also assumes the environment temperature is less than 250 ˚C and free of concentrations of noble gases, and radioactive and other contaminants known to lower the corona inception voltage.

Typical problem areas are:

- Low voltage tracking across contaminated insulating surfaces where low current (nanoampere) may eventually char the insulation.
- Metal migration may occur over extended operating time resulting in a short circuit when the migrating metal bridges a gap between electrodes.
- Corrosion due to salt spray, outgassing products, and oils may create critical pressures that may affect nearby high voltage circuitry.

When the voltage stress in air is less than 50 V/mil (2,000 V/mm), creepage and tracking should not exist provided the following good workmanship practices are followed during design, packaging, assembly and test:

- Avoid contamination on conductor and insulation surfaces.
- Avoid short gaps between thinly insulated bare conductors.
- Select insulating materials with low dielectric constants, and maximum resistivity and dielectric strength.
- Base all calculations on the instantaneous peak abnormal over-voltage.
- Avoid sharp points and rough electrode surfaces.

B. 50 V to 250 V

This voltage range is usually considered corona-free for dc voltages and sinusoidal ac peak voltages with frequencies less than 50 kHz.

Typical problems for circuits in this voltage range are:

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14. ABSTRACT
A detailed knowledge of electrical insulation and high voltage design techniques is essential if reliable high voltage systems are to be designed and manufactured for use in sub-atmospheric environments. The trend is towards more advanced systems operating at higher voltages in compact, economical packages that have been submitted to a battery of diagnostic techniques to ensure a high quality assembly. The purpose of this paper is to present an overview of high voltage electrical/electronic design considerations required to specify and apply electrical insulation to high-voltage parts, components and systems used in sub-atmospheric environments. Operating voltage, frequency, temperature, ambient gas composition, pressure, radiation, and structural requirements must be known when designing insulation for high voltage equipment.

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- Corona, enhanced by the presence of concentrations of noble gases and hydrogen.
- Sharp edges on dielectrics (equivalent to sharp edges on metals).
- Over-tightened clamps and ties on shielded and unshielded insulated conductors resulting in over-voltage reflections and failures.

By assuring that the field stresses have a maximum value of less than 100 V/mil (4000 V/mm), breakdown should not occur when these practices are followed during design, packaging, assembly and test:

- Eliminate triple points by forming a small gap between the dielectric and the metal. A triple point is where a dielectric is joined to a conducting material in the presence of a gaseous or liquid dielectric.
- Recess terminals and encapsulate with void-free bonded potting materials.
-Lengthen flashover gaps with skirts, grooves, and undercuts.
- Use smooth rounded surfaces and edges wherever possible.
- Minimize capacitive coupling between circuits.
- Conformal coatings can protect the circuit from faults, eliminate moisture penetration, and be sufficient to inhibit glow discharges and corona.
- Separate high voltage and low voltage circuits as much as possible.
- High voltage wires and cables should be placed close to ground planes with sufficient insulation
- Avoid repeated dielectric withstanding voltage tests on components to prevent cumulative over-stress.

C. Voltages over 250 V

Most frequent failures for this voltage range include:

- Incomplete bonding of materials such as Teflon to epoxy.
- Partial discharges in voids within encapsulating materials caused by incomplete outgassing during processing.
- Cracked encapsulation by insufficient post encapsulation curing, specifically inadequate mechanical stress relief.
- Creepage and tracking.
- Insulation cracking and treeing caused by temperature stresses in materials with insufficient temperature coefficients of expansion.

This is the normal high voltage range where most problems exist due to voltage overstress, flashover and voltage breakdown. Design features to be added to the good workmanship and precautions described above are listed below.

- Eliminate voids. Small voids are subject to partial discharges; larger gaps may result in voltage breakdown leading to arcing and bulk discharges.
- Corona, partial discharges and glow discharges all have different frequency signatures. The test equipment must be selected to detect each specific phenomenon.
- Control magnetic fields near high voltage circuits. The breakdown voltage between conductors can be raised or lowered in the presence of a magnetic field.
- Subassemblies or circuits containing gas-filled volumes should be either filled with a dielectric gas or pressurized over-ambient with filtered air.
- Use lossy dielectric materials for shielding of high voltage conductors and parts.
- Polish conductors to eliminate all rough spots or jagged surfaces.
- Inspect for debonding of conformal coatings.

Hermetic sealing or total encapsulation may be required for circuits that operate at voltages above 5 kV and at pressures lower than 100 Torr (1×10^{-2} Pa). A gas with a high dielectric strength and large molecules, such as sulfur hexafluoride (SF_6), is recommended to assure leak-free operation for long periods of time.

II. FLASHOVER STRENGTH

Current flowing across the surface of an insulator, especially when slightly wetted and containing a conductive contaminant may produce enough heat to generate a track of carbon. This conductive path tends to reduce the capability of the insulator to hold off the voltage.

A. Effect of Dielectric Constant and Frequency

Flashover strength is affected by dielectric constant. High dielectric constant materials have much lower resistance to surface voltage creepage than the low dielectric constant materials. Figure 1 is an illustration showing the advantage in selecting the correct dielectric constant [1]. The flashover breakdown factor in the illustration represents the results of many measurements, showing how a decreasing flashover voltage can be expected across the dielectric when insulations of progressively higher dielectric constants are used.

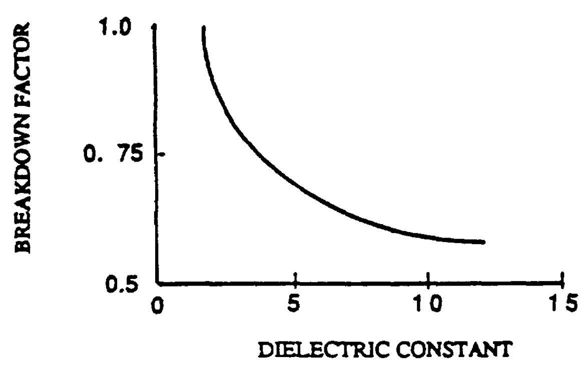

Figure 1. Variation of flashover voltage with changing insulation dielectric constant [1]

All materials have lower flashover strength at higher frequencies. Polyethylene (PE), which is representative of the low-loss, low dielectric constant class of material, exhibits the smallest decrease in flashover strength with

respect to increasing frequency. Table 1 shows the dielectric strength of PE as a function of frequency and temperature [1].

Table 1. Polyethylene dielectric strength (in V/mil) for 30 mil sheets as a function of temperature and frequency [1]

Temperature (°C)	Frequency				
	60 Hz	1 kHz	38 kHz	180 kHz	2 MHz
-55	1,660	1,270	750	700	410
25	1,300	970	500	460	340
50	1,140	910	590	580	280
80	980	970	440	430	220

B. Effects of Air Temperature and Humidity

It is useful to understand the relationship between flashover strength at 23°C and other temperatures. For gaseous breakdown in a uniform field, this relationship involves the ratio of the gas densities at the two temperatures. However, this may not hold true for surface flashover, because there are other factors such as outgassing, surface charging, and triple point effects involved in surface flashover events. As a rule the flashover voltage appears to increase as the rate of air convection in the system increases.

The flashover strength at 100% relative humidity (RH) is approximately 1/2 the strength at 0% RH. Ice and snow do not appreciably reduce the effective flashover strength. The selection of insulating materials resistant to surface wetting and moisture absorption will greatly facilitate the maintenance of original flashover strengths. A water-repellent treatment will aid on materials that are easily wetted.

III. BREAKDOWN OF SOLIDS

Solid insulating materials play an important role in electrical systems, because they act as mechanical support as well as electrical insulation.

A. Dissipation Factor and Polarization

Dielectric strength, dielectric constant, and the dissipation factor are the most readily measured electrical properties. Dielectric strengths and dielectric constants are well documented for high voltage materials. However fewer data are available on the dissipation factor, also called loss tangent, which is defined as $\tan\delta = \frac{\sigma}{\varpi\varepsilon}$, where σ is the ac conductivity, and ϖ is the frequency in radians/s. Dissipation factor and dielectric constant both vary with frequency and temperature. Elevated values of dissipation factor cause the dielectric heating in the insulation system and results in power loss. There are some frequency ranges for a given dielectric material that the dissipation factor is above the acceptable design requirements. The system should be operated in a regime where the dielectric constant has a constant value over the operating frequency and temperature ranges, and dissipation factor should be relatively low to avoid dielectric heating and instability of the impedances.

Dielectric materials used for electronic designs should be evaluated for a change of dielectric constant as a function of frequency to determine polarization effects. The dielectric constant of many materials as a function of frequency is given in [2]. The interfacial polarization is broadband and may be further broadened by wide temperature excursions. This implies that an electronic circuit should be evaluated through the full operating temperature range, instead of the temperature extremes, [3].

B. Dielectric Strength

The dielectric strengths of insulating materials quoted in manufacturers' literature are based on the statistical average breakdown of carefully manufactured, constant thickness samples. These values should be used with caution in equipment design because of the following reasons:

- Variation in manufacturing tolerances and compositions
- The manufacturers' data is based on testing at 23 ^{o}C
- Data is for a small surface area sample without voids
- Voltage transients are rarely considered
- Field stress variations with changes in electrode shapes are not considered
- The aging effects on dielectric strength are not considered

IV. RESISTIVITY

A high volume-resistivity reduces heating of the dielectric. Values greater that 10^{12} Ohm-cm are adequate for most power equipment. High-voltage insulation should have a volume resistivity, greater than 10^{14} Ohm-cm. Surface resistivity must be greater than 10^{9} ohm-cm to prevent tracking and surface flashover events. New insulations usually have surface resistivities greater than 10^{12} Ohm-cm at 23 ^{o}C and 50% relative humidity. This value becomes much lower at higher humidity and temperature values. If the surface resistivity is reduced from 10^{9} to 10^{8} by contamination, a significant surface leakage current will flow. This will form a "dry band" on the surface of the dielectric. In some cases, the dry band can be bridged by a small electrical discharge when the stress locally exceeds the breakdown stress of air at the air-solid interface. Consequently, local heat from the discharge will decompose the insulation and form a conducting path on the surface. With time, the paths will propagate, forming a tree, and eventual breakdown [4].

V. AGING

Aging is defined as the reflection of the chemical and physical changes, in electrical materials or electrical

systems, resulting from stresses with the passage of time Brancato [5]. This implies that there are several aging processes such as thermal, electrical, mechanical, radiation and chemical. Both thermal cycling and chronological aging diminish the dielectric and tensile strengths of dielectric materials and potted compounds.

Materials' aging is an estimation of probabilities rather than an exact science due to materials' chemical composition variables as well as processing and workmanship variables. The characteristic life of a material can be evaluated as a function of temperature when data are plotted as Arrhenius plots.

Most manufacturers' data provides only the one-minute dielectric strength test results conducted at 23°C and 60 Hz between 0.5-inch diameter electrodes, telling little or nothing about the aging characteristics of the material. Figure 2 shows aging data for a polyethylene film exposed and unexposed to corona at two different operating temperatures [6].

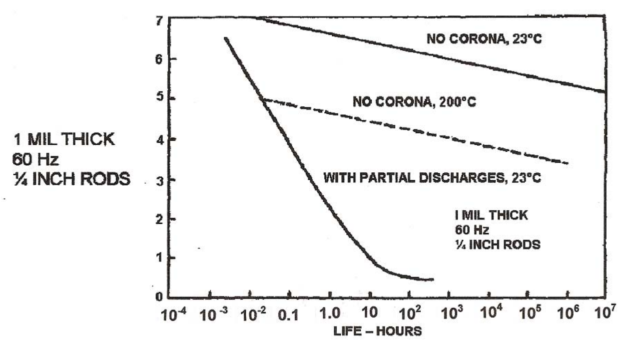

Figure 2. Life as a Function of Voltage for Type H Kapton

Table 2 shows the maximum field stresses for 1 hour of operation of three generic-type encapsulating materials [7]. Note that the data in Table 2 are for 1 hour lifetime. To obtain 10,000 hours the maximum stress must be decreased considerably. The voltage stress must be decreased by 8 to 10 % for each order of magnitude increase in service life. For 10,000 hours the stress should be decreased to about 65 % of the values shown in Table 2

Table 2. One Hour Life Field Stress.

Materials	Maximum Field Strength (V/mil)
Epoxies	200 to 350
Silastics	300 to 600
Urethanes	250 to 500

VI. CONCLUSIONS

It is recognized that this paper is not a comprehensive "how-to" guide for insulation design in sub-atmospheric pressures. However, the basic principles and design philosophy have been presented in an attempt to provide guidance to design engineers. If needed, further details can be obtained from the references.

VII. ACKNOWLEDGEMENT

This paper is based on private communications with William G. Dunbar in the course of his work on previous high voltage design criteria documents [6, 8]. The majority of the information contained therein was provided by W. G. Dunbar, calling on his vast working knowledge of high voltage equipment design for aerospace systems. (He was working on a revised edition prior to his passing in 2000.) This knowledge, set down in this paper and other design guides, is still useful in current and future design processes for advanced electrical/electronic equipment that must operate in sub-atmospheric environments.

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